FPD China 2014

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Selecting Transparent Conductors for Touch

Introduction…1

- Metal mesh (silver & copper)
- Silver nanowires
- Carbon nanotubes (“CNTs”)
- Conductive polymers (PEDOT)

- But not graphene…yet

Introduction…2

- **Intel does NOT have a “favorite” transparent conductor**

- **Intel likes them all because (depending on the selection) they offer…**
  - Lower cost
  - Higher performance
  - New capabilities

- **The goal of this presentation is to explore <u>what to consider when selecting a transparent conductor</u>, NOT to recommend the best one**

Introduction…3

❖ Caution!

- You must assume that every supplier is not truthful about competitive materials or suppliers
- All material comparison-charts are "rigged" in favor of the creator, out of date, or just plain wrong
- This is "business as usual" for marketing technical products, but the amount of misinformation circulating about transparent conductors seems unusually high

***Note:** This market is highly competitive and secretive, so there may be errors in my presentation!*

Factors To Consider

- Optical performance
- Electrical performance
- Physical characteristics
- Reliability
- Cost

Optical Performance…1

- **Visibility in front of LCD**
  - Nano: Conductor size is too small to see
  - Micro: Wider conductors (e.g., 3-6 microns) visibly block light from LCD
    - Conductors are currently ~3 µm, heading for 1 µm or less
- **Transparency**
  - For opaque conductors, it's how much open area is available
    - Nano: Hard to calculate; just measured
    - Micro: Simple geometry calculation – but you need to know if the two meshes are aligned or staggered
  - For true transparent conductors (e.g., polymers), it's the transmissivity

Optical Performance…2

- **Effect of ambient light**
  - Nano: More reflective wire-surfaces tends to increase haze
    - Substrate film also contributes to haze
    - CNTs have the lowest reflectivity of all
  - Micro: Anti-reflective coating (e.g., black ink) on conductor varies in effectiveness
    - Coating may not cover the sides of the conductor
    - Nobody (yet) can coat the underneath of the lower conductor on a double-sided film
    - Nobody (yet) has a good solution for reducing visibility outdoors (i.e., in very strong ambient light)

Optical Performance…3

Moiré patterns

- Nano: Random conductor-arrangement and nano scale prevents the problem
- Micro: Some (but not all) suppliers have 100% eliminated moiré patterns, even at 400 ppi, using algorithms that adjust mesh spacing and angle relative to the LCD pixel structure so that the resulting interference frequencies are not visible
  - However, this makes the sensor pattern unique to a specific LCD or family of LCDs

Color shift

- ITO: Well-known for yellow color shift ($b^* > 2$)
- Silver & polymer: Moderate ($1 < b^* < 2$)
- Copper & CNTs: Lowest ($b^* < 0.5$)

Electrical Performance

- **Sheet resistivity is a very important specification**
  - Sheet resistivity is a function of the material resistance and the conductor cross-section area
    - Sheet resistivity continues to decrease in general
    - Lowest to date is <1 Ω/□ (probably at 88% transparency)
  - For larger screens, low sheet-resistivity allows...
    - Charging the capacitors (electrode intersections) faster, which allows…
      - Sensing more electrodes in a given amount of time, OR
      - Taking less time to do the sensing (less subject to noise), OR
      - Increasing the frame rate (samples per second)
  - For smaller screens, low sheet-resistivity isn’t that important
    - Conductive polymers and CNTs work well

Physical Characteristics…1

- **Flexibility**
  - "Conformable": Bend once in manufacturing, or at very low radius on the user's wrist
  - "Rollable": Bend 10K times at 4-25 mm radius
  - "Foldable": Bend >100K times at <1 mm radius
    - CNTs & polymers: Best
    - Nanowires: Better
    - Micro mesh: Good
    - ITO: Poor, unless it's in a structure that eliminates all stress (ITRI, 2013 – interesting lab experiment; impractical in the real world)
- **3D-formed designs**
  - Most materials can do this today
    - Some are easier to do it with than others

Physical Characteristics…2

- **Narrow borders**
  - Mostly a function of manufacturing method for the routing traces
    - Photolithography
    - Gravure printing
    - Flexographic printing
    - Screen printing
      - Starting to see printing of conductive inks color-matched to decoration; eliminates need for silver
- **True single-layer sensors**
  - "Borderless" is another name for single-layer (all traces on one end)
    - Nano-scale may be better for borderless due to lack of visibility
  - ITO isn't rolling over and giving up
    - True single-layer ITO sensors in the "caterpillar" pattern that support 2 or 3 reliable touches are becoming common in low-end phones; reported sensor film cost in China is $0.70 for 4.3 inches on PET

Physical Characteristics…3

- **Double-sided sensors (GF2)**
  - Some suppliers are not equipped to pattern/print both sides of a single piece of film, so it's common to see GFF type of structures
    - 2X film cost, 2x lamination & OCA cost, possibly lower yield
- **Routed sensor with integrated tail**
  - It's possible to pattern the touch electrodes, routing traces, and sensor-tail connections all in one process (but not one step)
    - Reduces cost by eliminating processes
- **Thinner cover glass**
  - Some suppliers claim that the physical arrangement of their metal-mesh touch electrodes allow thinning the cover glass from 0.55 mm to 0.4 mm due to e-field uniformity

Reliability

- **Metal-mesh redundancy**
  - “Grid” touch-electrode pattern provides multiple conductive paths in each electrode so that if one path breaks it has no effect
  - “Diamond” touch-electrode pattern reduces redundancy significantly at narrow crossovers (8-10x → 2.5x)

- **Metal mesh corrosion**
  - Hard-coat on substrate may eventually result in metal corrosion and/or peeling

- **Long-term environmental tests**
  - Done only by some suppliers; too soon for reliable results

Cost…1

- **Material cost**
  - Silver costs more than copper, but in the amounts used the difference doesn't seem to be very significant
- **Patterning method**
  - Photolithography + wet etching
    - Traditional & most common method but most expensive
  - Laser etching
    - Cost and TACT time is rapidly dropping (especially with multi-head lasers); a 4.3" ITO phone-sensor can now be patterned in <4 seconds with a single-head 10-watt laser
    - CNTs can be laser-patterned very quickly due to carbon material
  - Gravure or flexographic printing
    - Current low-cost methods gaining traction
  - Micro-contact printing (also called "nano-imprinting")
    - Uses PDMS stamp; also low-cost

Cost…2

- **TACT time**
  - Function of patterning method and total number of process steps
    - "Roll-to-roll" photolithographic patterning for mesh is typically "advance the roll then pause for ~10 seconds"
    - Roll-to-roll processing for silver nanowires is continuous
- **Manufacturing CAPEX**
  - More expensive manufacturing methods (e.g., photolithography + etching) require more expensive capital equipment, including waste-water processing
    - Equipment depreciation is part of the product cost
    - The difference in CAPEX between methods can be 5X or more

Cost…3

- **Business model**
  - Sensor-film only supplier
  - More vertically integrated sensor/module supplier

- **Product cost**
  - Market pricing: Undercut ITO just enough to get the business
  - Margin pricing: Make a reasonable margin over your costs
  - Get-the-business pricing: Sell at or below cost if necessary

- **Current oversupply condition in >10-inch sensors may be distorting the pricing picture**

Example Suppliers & Production Methods…1

- **Copper mesh**
  - Atmel: Photolithography
  - LG Innotek: Photolithography or nano-imprinting
  - Unipixel: Flexographic printing

- **Silver mesh**
  - O-Film: Gravure printing
  - LG Innotek: Photolithography or nano-imprinting
  - FujiFilm: Photographic (silver halide) process; requires silver recovery due to amount of silver used
  - Cima NanoTech: Self-assembling random silver mesh starting from liquid coating
  - ClearJet: Inkjet-printed "coffee rings"

Example Suppliers & Production Methods…2

- **Silver nanowires**
  - Cambrios: Ink-focused
  - Clearstream: Solution-processed film-focused
- **Carbon nanotubes**
  - Canatu: Proprietary dry-coated film followed by laser etching
- **Conductive polymers**
  - Heraeus/Kodak: Printable with slot-die, dip, flexographic, gravure, inkjet, spin-coating

Recommendations

- **Discard all supplier-generated comparison charts and create your own**
  - Include all the considerations in this presentation
  - Only trust information from a supplier on their own product

- **Prioritize your detailed needs**
  - Optical, electrical, cost, etc.

- **Consider multiple suppliers for each material and each production method**

Conclusions

- **Transparent-conductor technology is still moving <u>very</u> fast**

- **Buyer beware – do your homework!**

Thank You!

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